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## Dusty disks at the bottom of the IMF

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### ABSTRACT

'Isolated planetary mass objects' (IPMOs) have masses close to or below the Deuterium-burning mass limit ( $\sim 15 M_{\text{Jup}}$ ) – at *the bottom of the stellar initial mass function*. We present an exploratory survey for disks in this mass regime, based on a dedicated observing campaign with the Spitzer Space Telescope. Our targets include the full sample of spectroscopically confirmed IPMOs in the  $\sigma$  Orionis cluster, a total of 18 sources. In the mass range  $8 \dots 20 M_{\text{Jup}}$ , we identify 4 objects with  $> 3\sigma$  colour excess at a wavelength of  $8.0 \mu m$ , interpreted as emission from dusty disks. We thus establish that a substantial fraction of IPMOs harbour disks with lifetimes of at least 2-4 Myr (the likely age of the cluster), indicating an origin from core collapse and fragmentation processes. The disk frequency in the IPMO sample is  $29 \pm_{13}^{16}\%$  at  $8.0 \mu m$ , very similar to what has been found for stars and brown dwarfs ( $\sim 30\%$ ). The object S Ori 70, a candidate  $3 M_{\text{Jup}}$  object in this cluster, shows IRAC colours in excess of the typical values for field T dwarfs (on a  $2\sigma$  level), possibly due to disk emission or low gravity. This is a new indication for youth and thus an extremely low mass for S Ori 70.

*Subject headings:* stars: circumstellar matter, formation, low-mass, brown dwarfs – planetary systems

## 1. Introduction

Over the past five years, it has been firmly established that the evolution of brown dwarfs from 1-10 Myr follows the blueprint known from T Tauri stars: They show evidence for ongoing gas accretion and outflows (e.g. Muzerolle et al. 2005; Mohanty et al. 2005), and harbour circum-sub-stellar disks with lifetimes of 5-10 Myr (e.g. Jayawardhana et al. 2003; Scholz et al. 2007), not vastly different from stars. This has often been interpreted as an indication for a common origin of stars and brown dwarfs – sub-stellar objects as the natural extension of the stellar initial mass function (IMF) and the lowest-mass outcome of core collapse and fragmentation processes (see review by Luhman et al. 2007, and references therein). At the same time, ongoing deep surveys have pushed the sensitivity limits down to masses below the Deuterium burning limit at  $\sim 15 M_{\text{Jup}}$ , finding evidence for a cluster population with masses comparable to giant planets (Zapatero Osorio et al. 2000; Lucas & Roche 2000). These objects *at the bottom of the IMF* are inconsistently called planemos, sub-brown dwarfs, cluster planets, or isolated planetary mass objects in the literature; in the absence of a definite nomenclature, we will use the latter term (abbreviated IPMO) in the following.

The nature and origin of IPMOs have been debated intensely in recent years. Most of the problems raised in the discussions about the formation of brown dwarfs apply even more acutely to IPMOs (see review by Whitworth et al. 2007). For example, it is under debate whether IPMOs can form directly from the collapse of ultra-low mass cores; instead, they may be giant planets ejected from circumstellar disks or stellar embryos ejected from mini-clusters or decaying multiple systems.

As of today, the observational constraints on the nature of IPMOs are very limited. Evidence for accretion or disks has been reported for a few young sources with masses around the Deuterium burning limit (Natta et al. 2002; Zapatero Osorio et al. 2002a; Luhman et al. 2005; Allers et al. 2006; Jayawardhana & Ivanov 2006). The next step is clearly to establish frequency and lifetimes of IPMO disks, and to push the mass limits of disk surveys towards the least massive objects in star forming regions. Here we present a Spitzer survey for disks around IPMOs in the  $\sigma$  Orionis cluster, which harbours the largest IPMO population identified thus far. With a well-explored stellar and brown dwarf population (Béjar et al. 2001; Caballero et al. 2007) and a likely age of 2-4 Myr (Zapatero Osorio et al. 2002c; Sherry et al. 2004),  $\sigma$  Ori is ideal for probing the disk frequency as a function of mass as well as the longevity of IPMO disks.

## 2. Observations and photometry

As part of the Spitzer program #30395 (PI: A. Scholz), we obtained deep IRAC images in the four channels centered at 3.6, 4.5, 5.8, and  $8.0\,\mu\text{m}$  for 18 objects in the  $\sigma$  Ori cluster with estimated masses below  $20\,M_{\text{Jup}}$ . All targets have been identified initially in deep photometric surveys (Zapatero Osorio et al. 2000, 2002b; Caballero et al. 2007). With one exception, all objects have been confirmed as likely ultra-low mass young cluster members with low-resolution spectroscopy; however, given the low signal-to-noise of the spectra, this should not be taken as a definite membership confirmation. In particular, the membership is under debate for S Ori 70 (see Sect. 4) and S Ori 47 (McGovern et al. 2004). See Table 1 for more information and references for the target properties.

The objects, covered with 13 IRAC fields, were observed in a 12 position dither pattern with the medium scale and 100 sec integration time per position. In total, this gives 1200 sec on-source time per target in each channel, a factor 10 deeper (in signal-to-noise ratio) than the GTO/IRAC survey of this cluster (program #37, PI: G. Fazio, see Hernández et al. (2007)). For the analysis, we made use of the post-BCD mosaics provided by the IRAC pipeline version S15.3.0. While parts of some images are affected by saturation effects and straylight from bright stars, in the regions where our targets are located the image quality is in most cases excellent.

All objects are detected in channels 1 and 2; two are not detected in channel 3 while four are invisible in channel 4. For the object S Ori 54, we used the publicly available GTO survey data to measure fluxes in channels 1 and 2, because in our deep images the source is ‘drowned’ in the emission from a nearby extended object and two nearby point-sources (all within  $8''$ ). The object S Ori 66 is located on a dark row in our IRAC1 and 2 images; again we obtained fluxes for this object from the GTO data.

Fluxes were measured by aperture photometry with relatively small apertures (3-5 pixels) using routines in *daophot*. For all objects, the aperture is free from visible neighbours. Aperture corrections were applied, as given in the IRAC data handbook (V3.0). Fluxes were converted to magnitudes using the recommended zeropoints quoted in the data handbook. All IRAC magnitudes for the IPMOs are reported in Table 1.

The dominant error source is background uncertainty. To get a realistic estimate, we measured the flux in empty regions in our images using the same method as for the targets ( $>50$  measurements in IRAC1 and 2,  $>80$  in IRAC3 and 4). As expected, these values scatter around zero; their rms defines the uncertainty in flux measurements due to background noise and small-scale fluctuations, and thus gives a conservative estimate on the photometric error for faint sources. We obtain 1.8, 2.2, 12.7,  $20.3\,\mu\text{Jy}$  in channels 1-4, respectively. Note that

these values do not correspond to the detection limits, which are better defined using the peak count rate of the PSF in comparison with the background scatter in the sky annulus. All objects for which fluxes are given in the tables are detected with a signal-to-noise-ratio of at least 4.

The total errors quoted in Tables 1 are comprised of photometric errors and systematics. The latter ones are the combination of uncertainties in calibration (5%) and aperture correction (1-2%, from the IRAC data handbook). No colour correction was carried out; instead we added a small contribution (0-2%) to the error budget. The upper limits quoted in Tables 1 correspond to three times the photometric errors. In channels 1 and 2, our fluxes are in excellent agreement (within 0.2 mag) with the values reported recently by Zapatero Osorio et al. (2007) for a subsample of our targets. In channels 3 and 4, the magnitude differences between our work and Zapatero Osorio et al. (2007) typically remain within 0.6 mag, still within the  $1\sigma$  errorbars. We note, however, that in these two bands our fluxes are in most cases substantially lower than the values given by Zapatero Osorio et al. (2007).

### 3. Disk Frequency in the Planetary Mass Regime

We search for mid-infrared emission from dusty disks in our sample by comparing the measured IRAC colours with published values for (disk-less) field objects in the same  $T_{\text{eff}}$  range (Patten et al. 2006). The main discriminators to distinguish between the photospheric contribution and the disk excess are the fluxes in the IRAC channels 3 and 4; at shorter wavelength the contrast between the photosphere and a possible disk is difficult to detect. In Fig. 1 we plot IRAC colours (I1-I4 and I1-I3) for all targets (except S Ori 70, see Sect. 4). As abscissa in these plots we use the  $I - J$  colour, which can be assumed to be purely photometric and thus represents a proxy for  $T_{\text{eff}}$ , which in turn correlates with mass for coeval objects. The plot covers a mass range from  $\sim 20$  to  $\sim 8 M_{\text{Jup}}$ . IPMOs are shown as crosses; the solid lines are linear fits to the colours of the field objects and thus delineate the photospheric level in these figures.

As can be seen in this plot, the majority of the IPMOs have IRAC colours indistinguishable from the photospheric values and can thus be assumed to have either no disk or only small amounts of dust in the inner disk. Sources that lack excess in our data include S Ori 54, S Ori 55, S Ori 56 for which Zapatero Osorio et al. (2007) reported disk detections based on the shallow GTO IRAC images. If we use the IRAC3 colour as disk criterion (upper panel), we find that four objects – S Ori 71, S Ori 60, S Ori 66, S Ori 58 – show excess at the  $3\sigma$  level, i.e. 4 out of 17 or  $24 \pm_{11}^{13}\%$ . Since disk excesses may appear only beyond  $5.8 \mu m$ , the result

from IRAC3 should be considered to be a lower limit.

Based on the IRAC4 colour (lower panel), we find four sources – S Ori 71, S Ori J053949.5-023130, S Ori 60, and S Ori 65 – with  $> 3\sigma$  colour excesses, which we consider to be primary disk detections.<sup>1</sup> In all four cases the excess increases significantly in IRAC channel 4 compared with channel 3, indicating rising flux levels towards longer wavelengths, a clear signature of disk emission. With the exception of S Ori 65, these objects have been published previously as disk-bearing very low mass sources (Caballero et al. 2007; Zapatero Osorio et al. 2007). This gives a disk fraction of 4 out of 14 or  $29 \pm_{13}^{16}\%$ . Here we do not count the three objects with upper limits well-above the photospheric level, for which we cannot decide if they have disk excess or not. Disk frequencies derived from IRAC3 and IRAC4 are thus consistent; since the value determined from IRAC4 is likely to be more robust, we put more emphasis on this result. We note that the disk fraction in our sample might still be somewhat higher than given here, due to the combined effects of photometric uncertainties and contaminating field objects (see the discussion in Caballero et al. 2007).

We now compare our disk detection rate with previous results for more massive objects in  $\sigma$  Ori, as given by Hernández et al. (2007) based on IRAC data: 15% for HAeBe stars, 27% for intermediate-mass T Tauri stars, 36% for T Tauri stars, 33% for brown dwarfs. The value for brown dwarfs is in agreement with the disk fraction of 33% derived by Jayawardhana et al. (2003) from ground-based L'-band imaging. A higher brown dwarf disk fraction of 47% has been published by Caballero et al. (2007). For the IMPO range (objects with  $M \lesssim 20 M_{\text{Jup}}$ ), we now derive a disk fraction of 29%, which is compatible with the values for T Tauri stars and brown dwarfs within the  $1\sigma$  uncertainties. We do not see a trend to higher disk frequencies in the IPMO range, as claimed by Zapatero Osorio et al. (2007), instead the evidence points to comparable disk fractions for planetary mass objects, brown dwarfs, and T Tauri stars, i.e. over more than two orders of magnitude in object mass ( $0.008 \dots 2 M_{\odot}$ ).

We note that two of the objects with disk excess, S Ori 66 and S Ori 71, stand out from the rest of the sample, as they show excessively strong  $\text{H}\alpha$  emission with equivalent widths of  $\sim 100$  and  $\sim 700\text{\AA}$ , respectively (Barrado y Navascués et al. 2001, 2002). This indicates that the presence of a dusty disks is likely accompanied by ongoing gas accretion, causing intense  $\text{H}\alpha$  emission, as observed in T Tauri stars and brown dwarfs.

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<sup>1</sup>The object S Ori 66, albeit having a high I1-I4 colour of 1.88 mag, is not counted here, because it has a large errorbar in IRAC4. A particular case may be the object S Ori 58, which does have excess in IRAC3, but appears below the photospheric level in IRAC4. This object has been identified to have a disk by Zapatero Osorio et al. (2007), based on a IRAC4 flux which is significantly higher than our measurement. Possible reasons for these ambiguous findings include significant background variations in that area, which might hamper accurate photometry.

#### 4. The case of S Ori 70

The faintest target in our sample, S Ori 70, has been reported originally as a  $\sim 3 M_{\text{Jup}}$  IPMO with tentative spectral type T5.5 (Zapatero Osorio et al. 2002b). If confirmed, it would be the lowest mass free-floating object found to date. Its mass would put it close to or even beyond the predicted opacity limit for fragmentation (see Bonnell et al. 2007, and references therein), and thus poses a challenge for star formation theory. However, Burgasser et al. (2004) have questioned the cluster membership (and thus the extremely low mass) of S Ori 70, and argue that its near-infrared spectrum is perfectly consistent with a foreground dwarf with spectral type  $\sim$ T6-7. In response, Martín (2004) reiterated the claim for cluster membership and youth mainly based on the  $(H - K)$  colour of S Ori 70, which is unusually high for a T dwarf, and is interpreted as evidence for low surface gravity. To date, the nature of this object remains unclear. Our deep IRAC images now allow a re-investigation of the issue.

S Ori 70 is clearly detected in IRAC channels 1 and 2. In addition, it is detected in IRAC3, with a  $\sim 4\sigma$  significance (peak countrate over background noise). The IRAC3 flux uncertainty has been derived based on the very fact that the object is just detected – if it were  $\gtrsim 25\%$  fainter than the estimated 17.2 mag, we would not be able to see it. In 2 we plot its IRAC colours vs. spectral type in comparison with measurements for field T dwarfs, taken from Patten et al. (2006). S Ori 70 is tentatively plotted spectral type T6 (average of the two available literature estimates).

As can be seen in this figure, the field T dwarfs form a clear sequence, whereas S Ori 70 stands out: In both IRAC colours, it appears to have some excess. Compared with the mean trend for the field T dwarfs, the significance of this excess is  $\sim 2\sigma$  in both IRAC2 and IRAC3. This excess cannot be accounted for by uncertainties in the spectral type, since the  $3.6 - 5.8 \mu m$  colour saturates in the late T dwarf regime and reaches maximum values of  $\sim 1.2$  – compared with 1.6 for S Ori 70. It should also be pointed out that S Ori 70 is brighter than the more massive L5 dwarf S Ori 67 in IRAC2 and 3, again indicating an unusual SED for this object.

There are two possible origins for a mid-infrared colour excess in S Ori 70: a) As reported by Leggett et al. (2007), gravity affects the near/mid-infrared colours of mid/late T dwarfs in the sense that it can produce a significant excess at  $2-6 \mu m$  for low-gravity objects. b) Similarly to the L type IPMOs in  $\sigma$  Ori, S Ori 70 might harbour a dusty disk, which produces the IRAC excess. Both possibilities provide additional evidence for youth, and thus the mid-infrared excess bolsters the claim that it is the lowest mass free-floating object identified thus far. In case the mid-infrared excess is due to a dusty disk, this can be interpreted as evidence for a star-like infancy. While the uncertainties in the IRAC fluxes are too large

at this stage for a definitive answer, these new findings certainly motivate further follow-up work on this target.

## 5. Summary

We have conducted a disk survey for isolated planetary mass objects, based on deep observations with the Spitzer Space Telescope. Our targets comprise the full sample of spectroscopically confirmed IPMOs in the  $\sigma$  Orionis cluster. As a pioneering study, the results presented here are not intended to be the last word on the subject. Instead, we intend this Letter to serve as an important step towards a more profound understanding of the nature and origin of the lowest mass objects found in isolation.

A substantial fraction of our targets exhibits mid-infrared excess emission indicative for the existence of a dusty disk. From our IRAC data, we derive a disk fraction of  $29 \pm_{13}^{16}\%$  (4/14) at  $8.0 \mu m$ . A similar value is found at  $5.8 \mu m$ . These results are fully consistent with the disk frequencies derived for T Tauri stars and brown dwarfs in the same cluster. The detection of dusty disks around IPMOs in  $\sigma$  Ori is another firm evidence for their nature as lowest mass members of this young cluster. The finding clearly establishes that objects at the bottom of the IMF can harbour dusty disks with lifetimes of at least 2-4 Myr, the most likely age of the  $\sigma$  Ori. Thus, our results fit into previous claims for a T Tauri-like phase in the planetary mass regime (Natta et al. 2002; Luhman et al. 2005; Allers et al. 2006; Jayawardhana & Ivanov 2006). Disk fractions and thus lifetimes are similar for objects spanning more two orders of magnitude in mass (0.008 to  $2 M_{\odot}$ ), possibly indicating that stars, brown dwarfs, and IPMOs share a common origin. Star formation theory thus has to account for a number of objects with masses below the Deuterium burning limit.

Our sample includes S Ori 70, the faintest candidate member so far in  $\sigma$  Ori, which is detected in our IRAC images from 3.6 to  $5.8 \mu m$ . Compared with field T dwarfs, the source stands out based on the IRAC colours, with excesses at 4.5 and  $5.8 \mu m$  at a  $2\sigma$  level. This may be an indication for youth and possibly disk occurrence for an object with an estimated mass of  $3 M_{Jup}$  (Zapatero Osorio et al. 2002b). Uncertainties are large, though, meaning that this should be seen as motivation for further follow-up rather than a definite confirmation of the ‘cluster planet’ nature of this object.

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Table 1. Targets and Spitzer photometry in the  $\sigma$  Ori cluster

Name	SpT <sup>a</sup>	I <sup>b</sup> (mag)	I-J <sup>b</sup> (mag)	3.6 $\mu$ (mag)	4.5 $\mu$ (mag)	5.8 $\mu$ (mag)	8.0 $\mu$ (mag)	comment
SOri71	L0	20.02	2.88	15.24 $\pm$ 0.06	14.83 $\pm$ 0.06	14.29 $\pm$ 0.08	13.84 $\pm$ 0.13	disk
SOri47	L1.5	20.53	3.15	14.87 $\pm$ 0.06	14.91 $\pm$ 0.06	14.77 $\pm$ 0.11	14.90 $\pm$ 0.33	
SOri50	M9	20.66	3.12	15.66 $\pm$ 0.06	15.64 $\pm$ 0.06	15.95 $\pm$ 0.30	15.63 $\pm$ 0.70	
SOri51	M9	20.71	3.50	15.42 $\pm$ 0.06	15.30 $\pm$ 0.06	15.19 $\pm$ 0.15	15.35 $\pm$ 0.51	
SOri53	M9	21.17	3.28	16.02 $\pm$ 0.06	15.84 $\pm$ 0.06	16.69 $\pm$ 0.63	15.47 $\pm$ 0.58	
SOri54	M9.5	21.29	3.30	15.8 $\pm$ 0.1 <sup>c</sup>	$\sim$ 15.6 <sup>c,d</sup>	$\sim$ 15.3 <sup>d</sup>	> 15.1	
SOri55	M9	21.32	3.10	16.41 $\pm$ 0.06	16.19 $\pm$ 0.07	16.18 $\pm$ 0.37	15.83 $\pm$ 0.90	
SOri56	L0.5	21.74	3.30	16.12 $\pm$ 0.06	15.79 $\pm$ 0.06	15.62 $\pm$ 0.22	15.27 $\pm$ 0.48	
SOri58	L0	21.90	3.30	16.43 $\pm$ 0.06	16.19 $\pm$ 0.07	15.52 $\pm$ 0.20	$\sim$ 16.7 <sup>d</sup>	disk?
SOri J053949.5-023130	NA	22.04	3.15	16.49 $\pm$ 0.06	16.32 $\pm$ 0.07	15.73 $\pm$ 0.25	15.05 $\pm$ 0.38	disk
SOri60	L2	22.75	3.58	16.61 $\pm$ 0.06	16.34 $\pm$ 0.07	15.34 $\pm$ 0.18	14.34 $\pm$ 0.20	disk
SOri62	L2	23.03	3.59	16.50 $\pm$ 0.06	16.36 $\pm$ 0.07	16.02 $\pm$ 0.32	$\sim$ 17.2 <sup>d</sup>	
SOri65	L3.5	23.23	3.33	16.72 $\pm$ 0.07	16.60 $\pm$ 0.08	16.05 $\pm$ 0.33	15.05 $\pm$ 0.38	disk
SOri66	L3.5	23.23	3.40	17.41 $\pm$ 0.1 <sup>c</sup>	16.87 $\pm$ 0.1 <sup>c</sup>	16.05 $\pm$ 0.33	15.53 $\pm$ 0.62	disk?
SOri67	L5	23.40	3.49	17.75 $\pm$ 0.10	17.64 $\pm$ 0.16	$\sim$ 17.6 <sup>d</sup>	> 15.1	
SOri68	L5	23.77	3.59	16.49 $\pm$ 0.06	16.39 $\pm$ 0.07	> 16.2	> 15.1	
SOri69	T0	23.89	3.64	16.87 $\pm$ 0.07	17.14 $\pm$ 0.12	> 16.2	> 15.1	
SOri70	T	25.03	4.75	18.83 $\pm$ 0.25	17.14 $\pm$ 0.11	$\sim$ 17.2 <sup>d</sup>	> 15.1	

<sup>a</sup>spectral types from Martín et al. (2001); Barrado y Navascués et al. (2001); Zapatero Osorio et al. (2002b); Barrado y Navascués et al. (2002)

<sup>b</sup>optica/NIR photometry from Zapatero Osorio et al. (2000, 2002b); Caballero et al. (2007)

<sup>c</sup>fluxes measured in GTO images

<sup>d</sup>uncertainty is approximately  $\pm 0.5$  mag

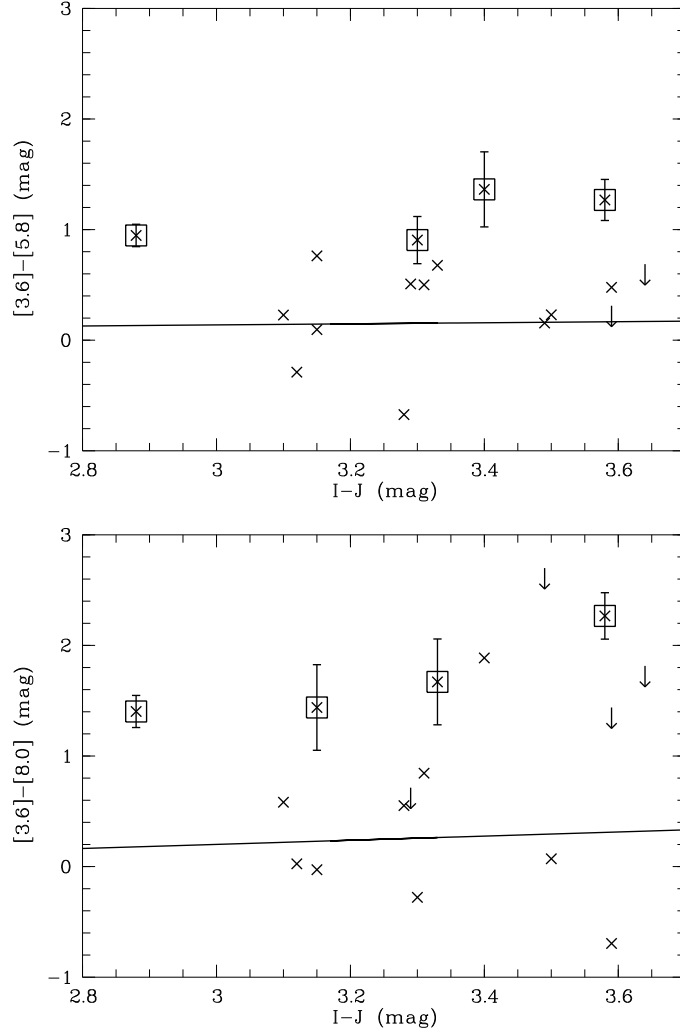


Fig. 1.— IRAC colours for IMPOs in  $\sigma$  Ori (crosses) in comparison with field M/L dwarfs (Patten et al. 2006, solid line). Objects with  $> 3\sigma$  excess with respect to the field dwarfs are marked with squares.

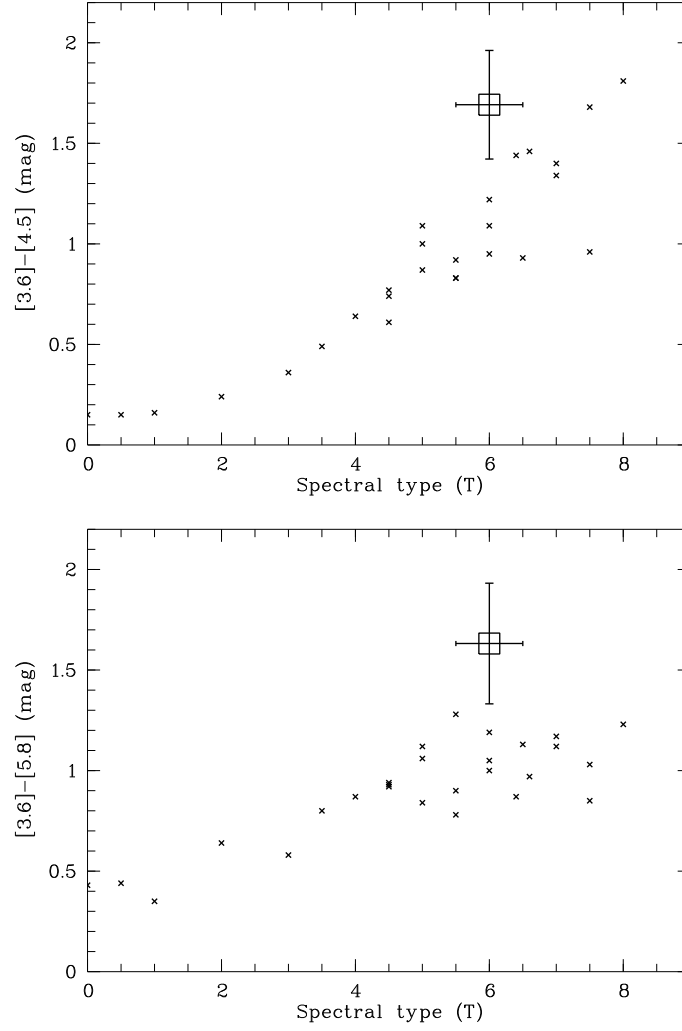


Fig. 2.— The IRAC colours of S Ori 70 (square) compared with field T dwarfs (Patten et al. 2006, small crosses).